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Ar-Ar age constraints on the timing of Havre Trough opening and magmatism.

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Abstract

The age and style of opening of the Havre Trough back-arc system is uncertain due to a lack of geochronologic constraints for the region. $^{40}Ar/^{39}Ar$ dating of 19 volcanic rocks from across the southern Havre Trough and Kermadec Arc was conducted in three laboratories to provide age constraints on the system. The results are integrated and interpreted as suggesting that this subduction system is young (< 2 Ma) and coeval with opening of the continental

Taupo Volcanic Zone of New Zealand. Arc magmatism was broadly concurrent across the breadth of the Havre Trough.

Keywords

Havre Trough, Kermadec Arc, Ar-Ar, magmatism, back-arc basin, rifting

Introduction

The present-day Kermadec Arc and associated Havre Trough back-arc basin is the youngest in a series of Cenozoic volcanic arcs that have developed along the northern New Zealand margin in response to convergence of the Pacific and Australian Plates (Mortimer et al., 2010; Herzer et al., 2011; Bassett et al., 2016). The Kermadec Arc - Havre Trough (KAHT) subduction system is the central portion of a contiguous arc system, with the Tonga Arc – Lau Basin back-arc system to the north, and the Taupo Volcanic Zone (TVZ) of continental New Zealand to the south (Figure 1) (Smith and Price, 2006). The predecessor to the Kermadec Arc, the Miocene-Pliocene Colville Arc (Skinner, 1986; Ballance et al., 1999), rifted apart in response to rollback of the Pacific Plate (Sdrolias and Muller, 2006; Wallace et al., 2009), forming the Havre Trough and resulting in the establishment of the modern Kermadec Arc front. The Colville Ridge and Kermadec Ridge are the remnants of the Colville Arc (Figure 1).

The age of opening of the Havre Trough and establishment of the Kermadec Arc is not clear owing to a paucity of age data. In part, this is due to the inherent difficulty in obtaining reliable radioisotopic ages on young, glassy, and vesicular submarine volcanic rocks with low potassium content, and in part due to tectonic complexity, and until recently, limited seafloor sampling in the region. Here, we present ^{40}Ar-^{39}Ar ages on seafloor volcanic samples from across the southern KAHT subduction system that have important implications for both the age and style of opening of the Havre Trough.

Models for opening of the Havre Trough

Several models have been proposed to explain the tectono-magmatic evolution of the Havre Trough and Kermadec Arc, but the process and timing of opening remains contentious. Malahoff et al. (1982), based on airborne magnetic studies and seismic lines over the southern and central portions of the KAHT, tentatively interpreted the Havre Trough to be undergoing spreading, centred on an axial ridge. They interpreted residual magnetic anomalies to indicate a ca. 1.8 Ma age of opening of the basin. Wright (1993), however, interpreted swath mapping data as showing that at least the southern Havre Trough lacked a medial spreading ridge, and hence interpreted back-arc rifting rather than spreading as the mode of extension. Further, Wright (1993), suggested that initiation of rifting occurred at ca. 5 Ma, although this age was constrained by extrapolation of geodetic data on continental New Zealand rather than on direct age data from within the Havre Trough.

Subsequent models for Havre Trough opening agreed that the system was rifting but have varied in the process and style of rifting being proposed. Wright et al. (1996) suggested that Havre Trough opening and magmatism progressed eastward with time. Parson and Wright (1996) further argued that there was a latitudinal progression from full oceanic spreading in the Lau Basin to the north, to basin rifting in the TVZ to the south. The southern Havre Trough was considered to be in an intermediate phase of rifting that was concentrated along the axial zone of the trough. Ruellan et al. (2003), on the basis of multibeam bathymetry and seismic reflection data, concluded that the southward propagation of spreading was oversimplified, and that southward migration of subduction of the Louisville Seamount Chain had effectively locked the KAHT. They proposed that opening of the Havre Trough was initially fast and pervasive, and then relatively quiescent as the system became locked. Wysoczanski et al. (2010), on the basis of morphological similarities, suggested that the Havre Trough was in a similar state of rifting to the Valu Fa Ridge and Western Lau Basin, and that it also was in a state of "disorganised spreading" (Martinez and Taylor, 2006) whereby diffuse patches of extension localised in deep rifts precedes longitudinally traceable axial ridges characteristic of true ocean spreading systems. This model reconciled the oceanic spreading model of Malahoff et al. (1982) with models of rifting, and is similar to the Parson and Wright (1996) final stage of rifting (their "Phase 4") preceding full spreading.

Analytical Methods and Results

A total of 19 volcanic rocks of variable composition dredged from across the KAHT (Table 1) have been dated by Ar-Ar step heating. The sample set is diverse, including samples from five arc front volcanoes, two volcanoes in the central Havre Trough (Gill and Rapuhia), a deep central Havre Trough basin (Ngatoro Rift) with a short axial ridge in its southern extent, and a cross-arc seamount chain (Rumble V Ridge) that spans the breadth of the Havre Trough, from Rumble V to the Colville Ridge (Figure 2). Geochemical data for all the samples have previously been reported, and the source of those data, together with new Ar-

Ar ages presented here, are shown in Table 1. With the exception of one andesite and one dacite from the volcanic arc front, all samples are basalts or basaltic andesites (Figure 3).

Ar-Ar analyses were performed in three laboratories (USGS, Menlo Park; New Mexico Institute of Mining and Technology (NMIMT), Socorro; and University of Wisconsin-Madison), initially as four smaller and separate studies. The datasets are combined here as one larger study to place constraints on the age of the KAHT (Table 1, Figure 2). All ages presented in Table 1 include 2σ uncertainties and full details of the analytical techniques are given in the Supplementary File.

The majority of ages for the arc front volcanoes are <0.06 Ma, although two samples, from Clark (C/1) and Rumble III (X333) have slightly older mean ages of 0.11 Ma and 0.12 Ma respectively. Uncertainties on arc front samples however are large, with most ages having 2σ uncertainties of zero age, and most ages are zero within analytical uncertainty.

Three samples from Rumble V Ridge have ages of < 0.11 Ma, overlapping those of the arc front volcanoes within uncertainty. The Ngatoro Rift samples have older ages between 0.20 Ma and 0.68 Ma.

To the north, two samples from Rapuhia Ridge, a volcanic ridge extending southwest from Rapuhia volcano in the centre of the Havre Trough, yielded ages of 0.05 $\pm$ 0.05 Ma and 0.11 $\pm$ 0.03 Ma. These ages are marginally older than, but within error of, ages derived from the active volcanic arc front. They are on average younger than the samples from Rumble V Ridge [see above], and notably younger than most of the Ngatoro Rift samples. Three samples analysed from Gill volcano, a back-arc volcano in the Havre Trough that lies between Rapuhia Ridge and the Colville Ridge (Figure 1), have ages significantly older than all other samples, at 0.88 $\pm$ 0.05 Ma, 0.97 $\pm$ 0.03 Ma and 1.19 $\pm$ 0.04 Ma.

Discussion

The presented Ar-Ar ages are from samples that span almost the entire width of the southern Havre Trough and thus provide important constraints on the manner and timing of its opening.

A first order observation is that the oldest ages reported here, from a back-arc stratovolcano (Gill volcano: Wysoczanski et al., 2010) in the western part of the Havre Trough, are 0.9 - 1.2 Ma (Table 1, Figure 2). However, because Gill volcano sits on a rifted basin floor, the implied age of rifting must be older. This age is similar to a preferred Ar-Ar age of 1.1 $\pm$ 0.4 Ma reported for a basalt from the western Havre Trough (Mortimer et al.,

2007) sampled 450 km to the north of, and along strike from, Gill volcano, and to a 1.25 ± 0.06 Ma U-Pb zircon age from a tonalite xenolith from Raoul Island (Mortimer et al., 2010). In addition, Mortimer et al. (2007) reported an Ar-Ar age of 1.2 Ma ± 0.8 for a basalt from the Northland Plateau (Figure 1), which they considered to be related to westernmost Colville Ridge volcanism. Together, these ages show no evidence for magmatic activity in the Havre Trough before c. 1.2 Ma, and as noted by Mortimer et al. (2010) suggest that magmatism was active across the full width of the KAHT and west of the Colville Ridge at this time (Figure 2). Furthermore, one of our plateau ages from Gill volcano is 875 ± 50 ka, and thus it is conceivable that the age of magmatism for the Havre Trough is younger than 1.2 Ma, and possibly < 1 Ma.

Using the 19 new Ar/Ar ages presented in this study and two previously reported by Mortimer et al. (2007; 2010), we now have sufficient geochronologic data to interpret the age of the Havre Trough. In addition, Ballance et al. (1999) reported eight K-Ar ages of c. 2 Ma or younger for the Kermadec Ridge and three K-Ar ages from the eastern Havre Trough, which were near zero age (the oldest at 0.15 ± 0.12 Ma). These ages for the Havre Trough are all significantly younger than the c. 5 Ma age of rifting proposed by Wright (1993). However, we note that all current age data are from surficial seafloor volcanics, and future sampling (especially from sub-seafloor drilling) may yield older ages that would require a reinterpretation of the results presented here.

The young age of magmatism, if correct, provides three important implications for the tectonic development of the Havre Trough.

Firstly, magmatism and translocation of the modern Kermadec Arc front did not occur in a monotonic eastward progression. Notably, there is near- zero age arc magmatism in the central portion of the Havre Trough at Rapuhia Ridge, and magmatism related to Rumble V Ridge does not young to the east (Figure 4). The Rumble V Ridge dates are younger in age than the Ngatoro Rift, indicating that the ridge may have been constructed over the Ngatoro Rift (and if this is correct, also the Rumble Rift), rather than being cut by rifting as previously suggested (Wright et al., 1996).

Second, reported age data for the Havre Trough is < 1.2 Ma, and possibly < 1 Ma. This is younger than, but broadly consistent with, the 1.8 Ma age of rifting suggested by Malahoff et al. (1982), although that model assumed a full spreading centre, whereas more recent tectonic models based on seafloor morphology suggest that the Havre Trough is comprised of a number of rifts and basal plateaus (e.g. Wright, 1993; Wysoczanski et al., 2010; Wysoczanski and Clark, 2012). These ages infer a c. 2.5-4 x faster extension rate for the Havre Trough than the 15-20 mm yr^{-1} rate suggested by Wright (1993). An age of 2 Ma would give an average rate of c. 40-50 mm yr^{-1}. Whilst reasonably fast, this rate is not unusual for extension rates in other intra-oceanic back-arc rifts, and is still significantly slower than the full ocean spreading rates of > 100 mm yr^{-1} occurring in the Lau Basin and Manus Basin (e.g. Taylor and Martinez, 2003; Heuret &Lallemand, 2005; Wallace et al., 2005). Notably this is similar to the extension rate of c. 40-60 mm yr^{-1} seen at the southern portion of the Lau Basin (Parson and Wright, 1996; Martinez and Taylor, 2001).

Third, opening of the Havre Trough is coeval with initiation of TVZ magmatism and rifting at c. 2 Ma (Wilson et al., 1995) and the TVZ rift and Havre Trough are the continental and oceanic expression of the same rift system (e.g. Parson and Wright, 1996). It is unclear if rifting was occurring prior to c. 2 Ma onshore in New Zealand: 1.8-3.9 Ma volcanism occurred along the Maungatautari-Kaimai-Tauranga alignment parallel to but northwest of the TVZ, as eruptions migrated southeast from the Coromandel area (Briggs et al., 2005). Given our ages for the Havre Trough, and that the youngest reported age of volcanism from the Colville Ridge is 2.6 Ma (Timm et al., in review), this magmatism is more likely to be related to Colville Arc magmatism rather than Havre Trough magmatism.

The western portion of the TVZ is the oldest part of that system (the “old TVZ” of Wilson et al., 1995, and Wilson and Rowland, 2016), and rifting is now focussed more to the east and along a central rift, variously defined as the “young TVZ” and “modern TVZ” (Wilson et al., 1995; Wilson and Rowland, 2016), Ruaumoko Rift (Rowland and Sibson, 2001) and the Taupo Rift (Villamor and Berryman, 2006). Whilst young arc magmatism is broadly occurring across the Havre Trough (Figure 4) we have insufficient data to identify any age progression of rift-related magmatism across the Havre Trough. It remains uncertain if eastern Havre Trough rift magmatism is younger than western Havre Trough rift magmatism, and so akin to the old and young/modern TVZ regions, respectively.

The present state of extension/rifting of the Havre Trough remains uncertain. In the case of the Ngatoro Rift, the ages presented here indicate prolonged magmatism over at least 0.4 Ma, and that the rift is not presently magmatically active at the seafloor. Importantly though there is extensive shallow seismic activity (< 13 km deep) within the Ngatoro Rift (de Ronde et al., 2007). Regional moment tensor analysis for recent (2003-2012) shallow (< 33 km) earthquakes in the southern Havre Trough show extension as well as strike slip movement (Ristau, 2014). At first order the shallow extensional seismicity in the Ngatoro Rift and elsewhere in the Havre Trough indicates present-day extension / rifting of the trough. Magmatic rift intrusives (e.g., dykes) may also be contemporaneous, however the absence of present day surficial extrusives and lack of hydrothermal activity suggests that seafloor, or near seafloor, rift magmatism is not occurring at the present day.

Conclusions

New Ar-Ar ages presented here, coupled with other published radioisotopic ages from the literature (Ballance et al., 1999; Mortimer et al., 2007, 2010), suggest that opening of the Havre Trough initiated < c. 2 Ma, and perhaps as recently as c. 1 Ma. The oldest ages occur on the margins of the basin and significant young arc magmatism occurred across the central Havre Trough. The timing of initiation of magmatism is coeval with that of the TVZ. The caveat to our age constraints is that all samples are surficial and there are no ages for samples within c. 25 km of the Colville Ridge (Figure 4).

Our results show that there has been arc and rift-related magmatism across the entire southern Havre Trough within the last c. 1 Ma, both within rifts (e.g., Ngatoro Rift) and constructing large stratovolcano cones such as Gill and seamounts of Rumble V Ridge (Wright e al., 1996; Todd et al., 2010). This, together with the >4 km water depth in the deepest parts of the basin, is more consistent with distributed rifting across the basin than ocean spreading. Whether there are differences in age between rift-related magmas erupted at different depths, or distance across the basin, or distance northward from New Zealand, is important for understanding the tectonic evolution of the basin but remains to be discovered. Our experience shows that $^{40}Ar/^{39}Ar$ ages can be obtained for the challenging Havre Trough samples, but that sample selection and treatment are important considerations.

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Figures

Figure 1: Tectonic setting of New Zealand and the SW Pacific highlighting the Kermadec Arc – Havre Trough (KAHT), the Tonga-Lau subduction system, and the Taupo Volcanic Zone (TVZ) of continental New Zealand (red outline). Black arrow is the relative motion of the Pacific Plate to a fixed Australian Plate for the southern KAHT region (DeMets et al., 2010). HP = Hikurangi Plateau, Louisville SC = Louisville Seamount Chain, NP = Northland Plateau, VFR = Valu Fa Ridge. Red triangles denote oceanic volcanoes of the Kermadec Arc and Havre Trough, and the offshore TVZ (southernmost volcano, Whakatane). Highlighted area is that of Figure 2.

Figure 2: Bathymetric map of the southern KAHT system, bounded by the Colville Ridge to the west and the Kermadec Ridge to the east. Depths on the bathymetry scale are metres below sea level, with depths < 1500 m shown as 1500 m and depths > 3500 m shown as 3500 m. Orange triangles are volcanoes: C = Clark, G = Gill, R = Rapuhia, RIII = Rumble III, RIV = Rumble IV, RV = Rumble V, T = Tangaroa. Numbers in boxes denote new Ar/Ar ages (Table 1).

Figure 3: Silica content of samples analysed in this study with distance from the crest of the Kermadec Ridge.

Figure 4: Ar/Ar ages of Havre Trough samples (Table 1) with distance from the Kermadec Ridge crest. Error bars show 2 sigma uncertainties. Black diamonds are K/Ar ages of Ballance et al. (1999) from Kermadec Ridge and Havre Trough samples at least 300 km north of samples presented here. Grey square at ~80 km is an Ar/Ar preferred age for a basalt from the Havre Trough (Mortimer et al., 2007). Grey square at 0 km is a U-Pb age of zircon from a

tonalite from Raoul volcano (Mortimer et al., 2010), 600 km to the north of the study area, where the modern arc front sits on the Kermadec Ridge (Figure 1).

Table

Table 1: Details of samples analysed in this study. Ages are: P=plateau ages, I=Isochron ages, R=Recoil age (see Supplementary File for details). Supplementary File contains plateau and isochron ages and plots, experimental data including K/Ca ratio, MSWDs, number of steps, and total gas age; along with an explanation of experimental methods and machine data for individual heating steps within each experiment. Results have been recalculated to a consistent fluence monitor age equivalent to Fish Canyon sanidine at 28.198 Ma (Menlo Park) and at 28.201 Ma (NMIMT). All errors are 2σ. For four samples, X379, X690, X682, and X696 the mean age is negative, so the positive fraction of the age is reported as a maximum value (i.e. <xx Ma), calculated as the mean of the 2σ error. IGSN numbers are given for those samples that have been assigned numbers. Reference for geochemical analyses: 1, Gamble et al, 1997; 2, Wright and Gamble, unpublished data; 3, Gamble et al., 1993; 4, Todd et al., 2010; 5, Zohrab, 2017; 6, Todd et al., 2011. All geochemical data are reported as anhydrous, with Fe as FeO_{total}.

STATION	LOCATION	LATITUDE SOUTH	LONGITUDE EAST	DEPTH M	LAB	LAB NO.	IGSN	REF.	SiO_2 WT.%	MgO WT.%	K_2O WT.%	AGE Ma	
C/1	Clark	36.416	177.848	2040	NMIMT	Clark #45, 6696		2	50.75	9.46	1.57	0.11 ± 0.05	P
X299	Rumble III	35.749	178.498	717	NMIMT	Rumble III #1, 6692		2	52.61	4.44	0.58	0.04 ± 0.06	P
X333	Rumble III	35.715	178.528	565	NMIMT	Rumble III #8, 6695		2	52.14	6.72	0.48	0.12 ± 0.08	P
X351	Rumble IV	36.131	178.024	1258	NMIMT	Rumble IV #9, 6703		2	66.19	1.47	1.11	0.03 ± 0.02	P
X379	Rumble V	36.153	178.161	1619	NMIMT	Rumble V#23, 6694	JBG000010	2	54.00	3.51	0.60	<0.03	P
X407	Rumble V	36.133	178.202	750	NMIMT	Rumble V #26, 6704		2	53.95	3.52	0.61	0.01 ± 0.06	P
X427/A	Tangaroa	36.311	178.004	1781	NMIMT	Tangaroa #39, 6691		2	59.26	2.63	0.67	0.06 ± 0.07	P
X153/1	Ngatoro Rift	36.260	177.300	2640	NMIMT	11574 Ngatoro Rift, 6702	JBG00001C	3	51.01	8.22	0.41	0.20 ± 0.14	P
X158/1	Ngatoro Rift	36.154	177.428	2300	NMIMT	11580 Ngatoro Rift, 6701		3	52.04	7.05	0.52	0.60 ± 0.24	P
X185/1	Ngatoro Rift	36.660	177.150	2810	NMIMT	11616 S. Ngatoro Rift, 6693	JBG000016	3	52.41	4.86	0.55	0.35 ± 0.22	P
X168/1A	Ngatoro Rift	36.258	177.573	2960	Menlo Park	10Z0107	JBG000017	3	52.84	7.38	0.60	0.68 ± 0.16	R
X690A	Cross arc	35.960	177.942	1805	Menlo Park	10Z0105	JBG000001	4	47.23	14.9	0.32	<0.11	I
X682	Cross arc	35.968	178.023	1480	Menlo Park	10Z0106	JBG000007	4	51.13	8.17	0.42	<0.03	I
X696A	Cross arc	35.886	177.843	1680	Menlo Park	10Z0104	JBG00000J	4	48.94	8.46	0.28	<0.07	I
015-04	Rapuhia Ridge	34.794	178.445	1910	Menlo Park	15Z0332		5	51.04	9.65	0.75	0.11 ± 0.03	P
016-01	Rapuhia Ridge	34.798	178.442	1800	Menlo Park	15Z0334		5	49.60	9.99	0.49	0.05 ± 0.05	P
012-01	Gill	34.623	178.379	1146	Menlo Park	15Z0319		5	47.91	9.30	0.46	1.19 ± 0.04	P
011-04	Gill	34.607	178.389	1700	Menlo Park	15Z0318		5	51.22	8.07	0.75	0.97 ± 0.03	P
011-A	Gill	34.607	178.389	1700	Wisconsin	UW93C37	JBG00001K	6	53.64	6.59	0.77	0.88 ± 0.05	P

Ages are: P=plateau ages, I=Isochron ages, R=Recoil age (see Supplementary File for details). Supplementary File contains plateau and isochron ages and plots, experimental data including K/Ca ratio, MSWDs, number of steps, and total gas age; along with an explanation of experimental methods and machine data for individual heating steps within each experiment. Results have been recalculated to a consistent fluence monitor age equivalent to Fish Canyon sanidine at 28.198 Ma (Menlo Park) and at 28.201 Ma (NMIMT). All errors are 2σ. For the four samples X379, X690, X682, and X696 the mean age is negative, so the positive fraction of the age is reported as a maximum value (i.e. <xx Ma), calculated as the mean of the 2σ error. IGSN numbers are given for those samples that have been assigned numbers.
Reference for geochemical analyses: 1, Gamble et al, 1997; 2, Wright & Gamble unpublished data; 3, Gamble et al., 1993; 4, Todd et al., 2010; 5, Zohrab, 2017; 6, Todd et al., 2011. All geochemical data is reported as anhydrous, with Fe as FeOtotal (not reported here).

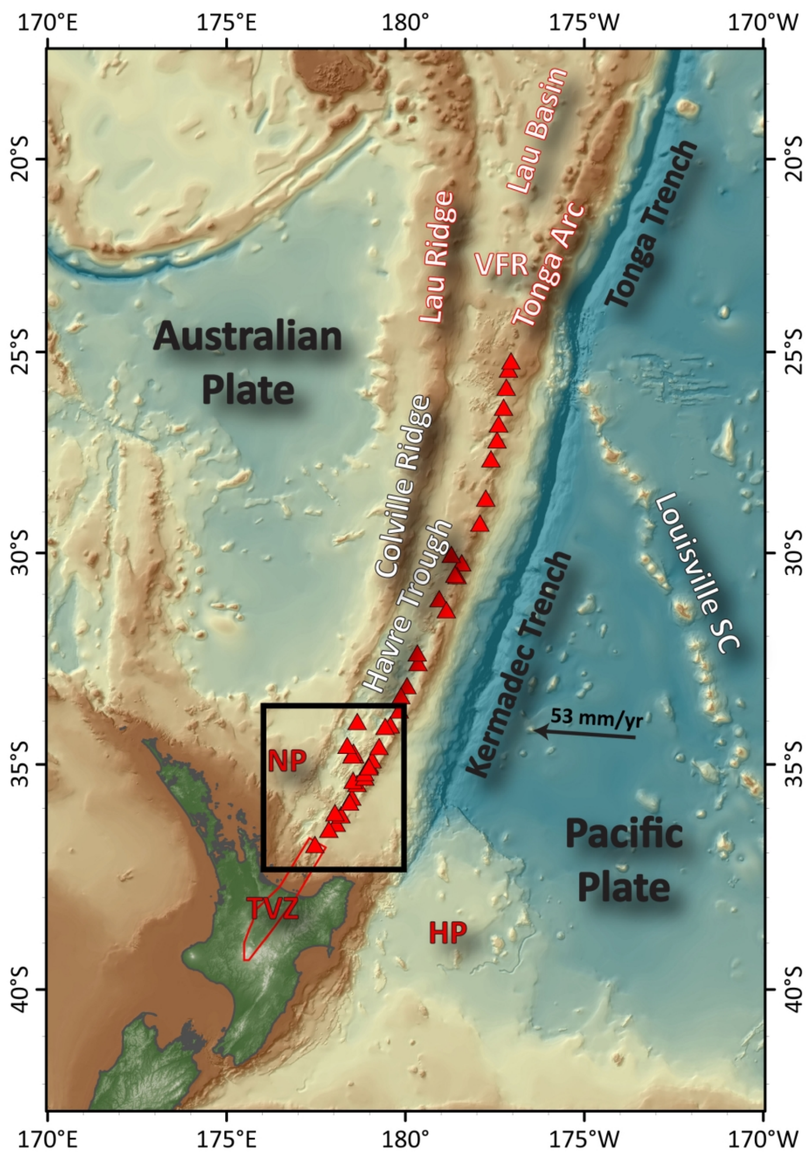

Figure 1: Tectonic setting of New Zealand and the SW Pacific highlighting the Kermadec Arc – Havre Trough (KAHT), the Tonga-Lau subduction system, and the Taupo Volcanic Zone (TVZ) of continental New Zealand (red outline). Black arrow is the relative motion of the Pacific Plate to a fixed Australian Plate for the southern KAHT region (DeMets et al., 2010). HP = Hikurangi Plateau, Louisville SC = Louisville Seamount Chain, NP = Northland Plateau, VFR = Valu Fa Ridge. Red triangles denote oceanic volcanoes of the Kermadec Arc and Havre Trough, and the offshore TVZ (southernmost volcano, Whakatane). Highlighted area is that of Figure 2.

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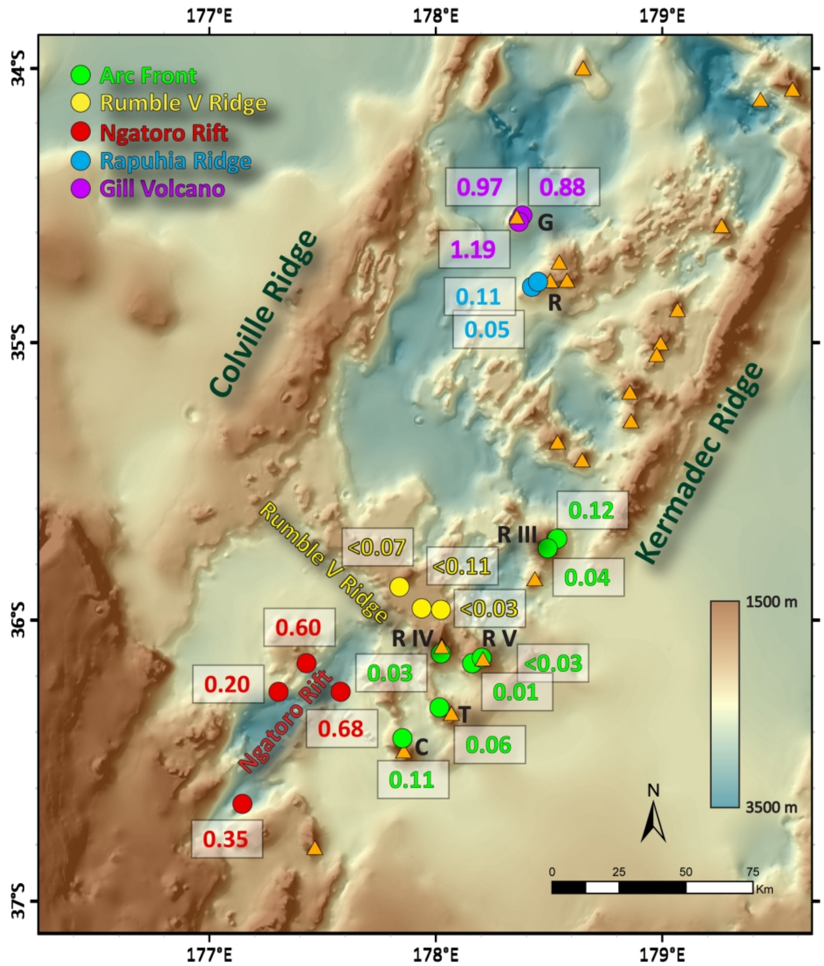

Figure 2: Bathymetric map of the southern KAHT system, bounded by the Colville Ridge to the west and the Kermadec Ridge to the east. Depths on the bathymetry scale are metres below sea level, with depths < 1500 m shown as 1500 m and depths > 3500 m shown as 3500 m. Orange triangles are volcanoes: C = Clark, G = Gill, R = Rapuhia, RIII = Rumble III, RIV = Rumble IV, RV = Rumble V, T = Tangaroa. Numbers in boxes denote new Ar/Ar ages (Table 1).

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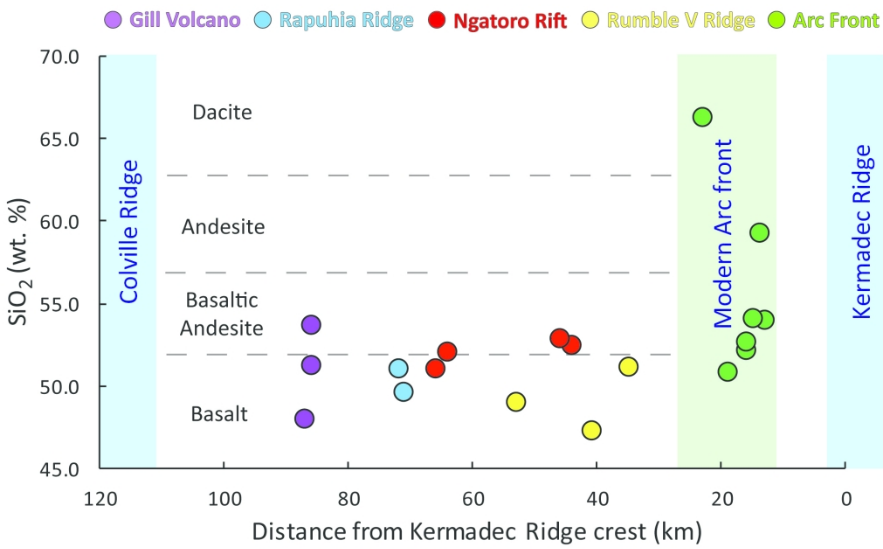

Figure 3: Silica content of samples analysed in this study with distance from the crest of the Kermadec Ridge.

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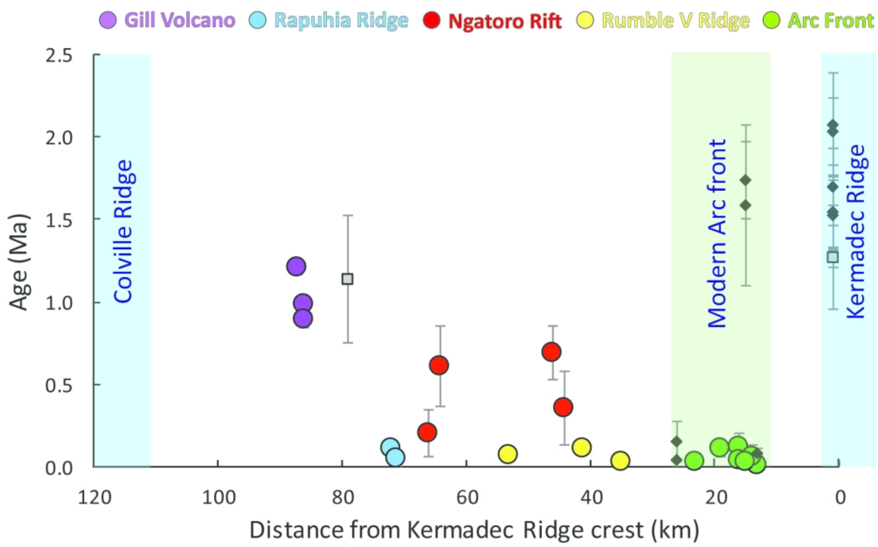

Figure 4: Ar/Ar ages of Havre Trough samples (Table 1) with distance from the Kermadec Ridge crest. Error bars show 2 sigma uncertainties. Black diamonds are K/Ar ages of Ballance et al. (1999) from Kermadec Ridge and Havre Trough samples at least 300 km north of samples presented here. Grey square at ~80 km is an Ar/Ar preferred age for a basalt from the Havre Trough (Mortimer et al., 2007). Grey square at 0 km is a U-Pb age of zircon from a tonalite from Raoul volcano (Mortimer et al., 2010), 600 km to the north of the study area, where the modern arc front sits on the Kermadec Ridge (Figure 1).

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